Pressure Vessel and Thermal Control Technologies

By

Dr. Mike Pauken

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, CA

Overview

- Introduction
- Discussion
  - Pressure Vessels
    - Historical Perspective
    - Design Guidelines
    - Candidate Materials
    - Material Down-Selection
    - Various Manufacturing Methods
  - Thermal Control Systems
    - Venera and Pioneer Venus
    - Insulation
    - Energy Storage
    - Active Control
- Summary & Conclusions

Introduction

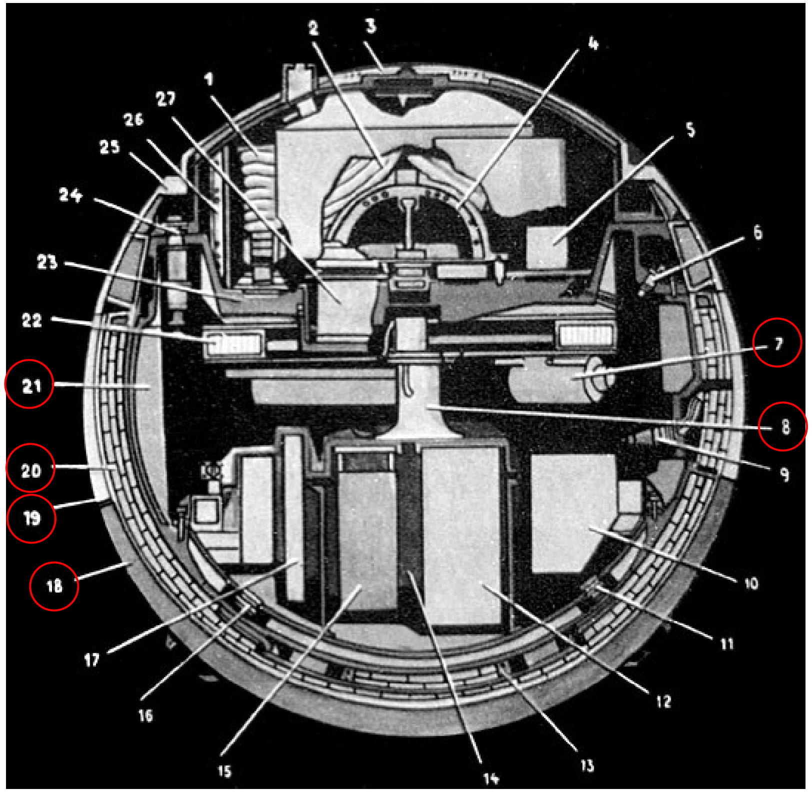
- Decadal Survey identifies Venus Lander, Jupiter Deep Probes as 2 of 6 highest priority missions
- Present state-of-the-art pressure vessel technologies are not adequate for the mass requirements of these missions
- The pressure vessel represents one of the single largest mass elements in a Venus Lander or Deep Atmospheric probe
- Several materials and manufacturing processes are available today with a potential to save mass in the pressure vessel
- Thermal systems have to isolate the Venus environment and absorb internally generated heat
- Previous Venus surface missions survived about 1 hour
- New missions will have to last from several hours to several days and will need passive or active thermal control systems

Historical Perspective

- Soviets began Venus exploration program with launch of Venera 1 in 1961. Program ended in 1984 with VEGA 1 and 2.
- NASA launched Pioneer Venus Probes in 1978

Mission	Launch Year	Pressure Rating
Venera 3	1965	5 bar
Venera 4	1967	20 bar
Venera 5,6	1969	25 bar
Venera 7	1970	150 bar Titanium
Venera 8-14	1972-1981	100 bar Titanium
Pioneer Large Probe	1978	100 bar Titanium
Pioneer Small Probe	1978	100 bar Titanium

Venera 5 Descent Module

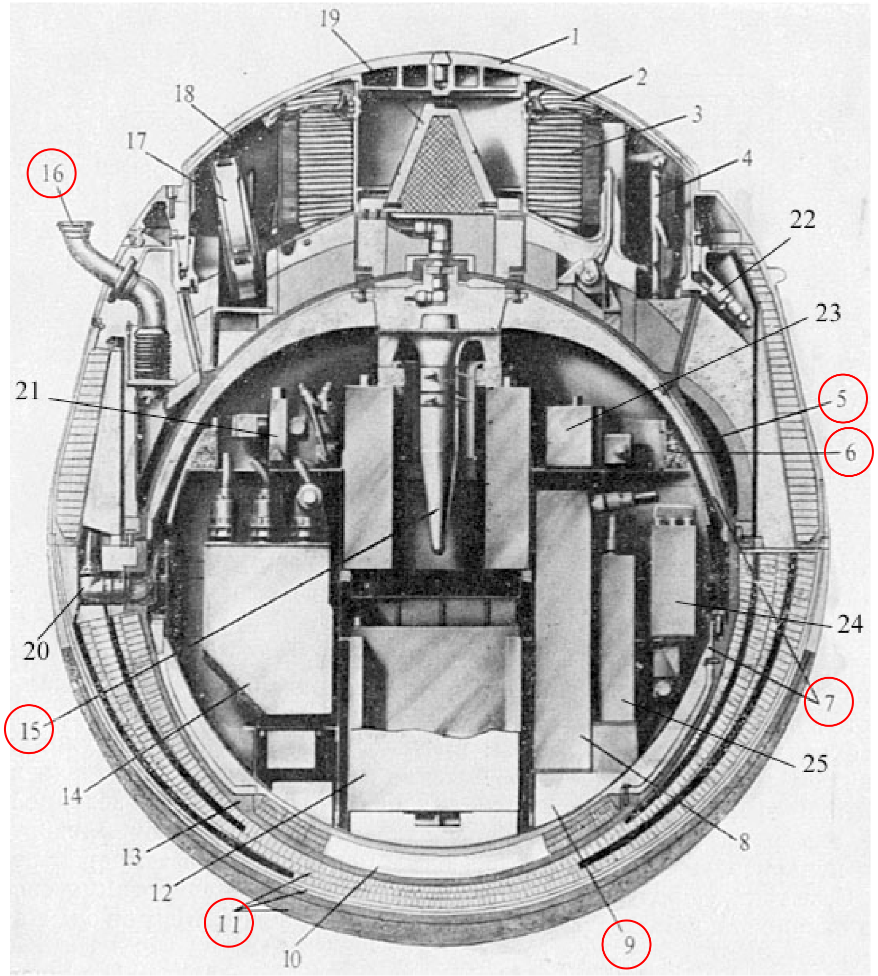


All systems, including instruments, were protected by pressure vessel and passive thermal control. Adapted from Ref 1.

The layout of the Venera-5 descent vehicle:

1. drogue parachute
2. main parachute
3. explosive bolts of cover
4. transmitter antenna
5. gas density gauge
6. grooving charge valve
7. **dehumidifier**
8. **circulation fan**
9. electrical umbilical
10. commutation unit
11. accelerometer
12. transmitters
13. anti-vibration damper
14. power unit
15. onboard transmitter
16. accelerometer
17. program timing unit
18. **heat shielding**
19. **heat shielding**
20. **external insulation**
21. **internal insulation**
22. temperature control system
23. lid of instrument compartment
24. explosive bolt
25. cover of parachute compartment
26. radio altimeter antenna
27. gas analyzer

Venera 8 Descent Module

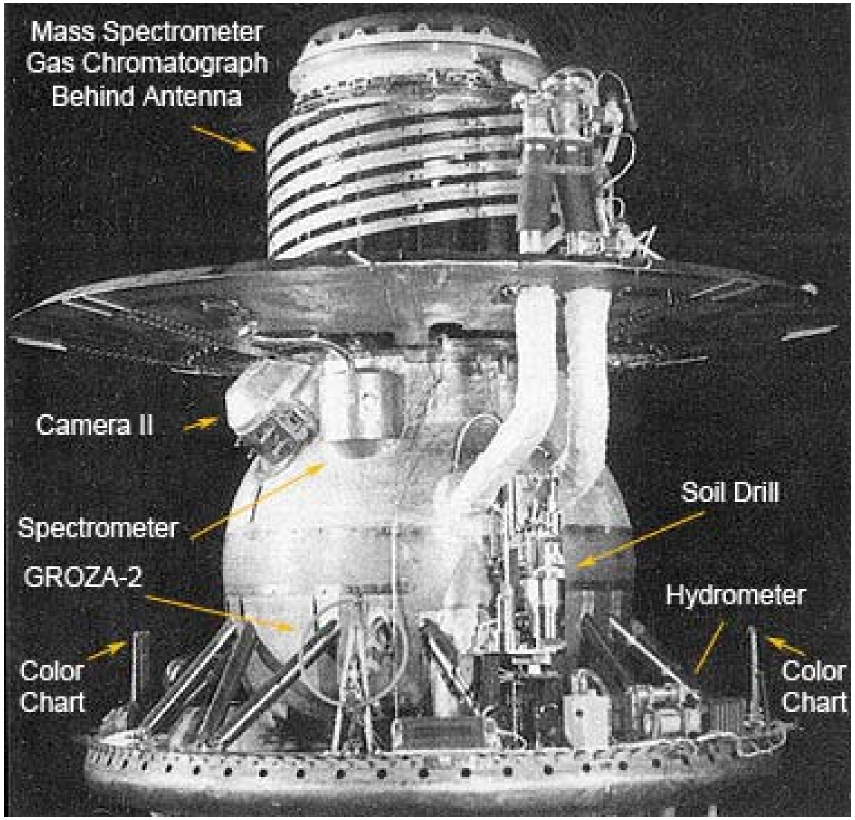


Adapted from Ref 1.

Venera 8 descent module:

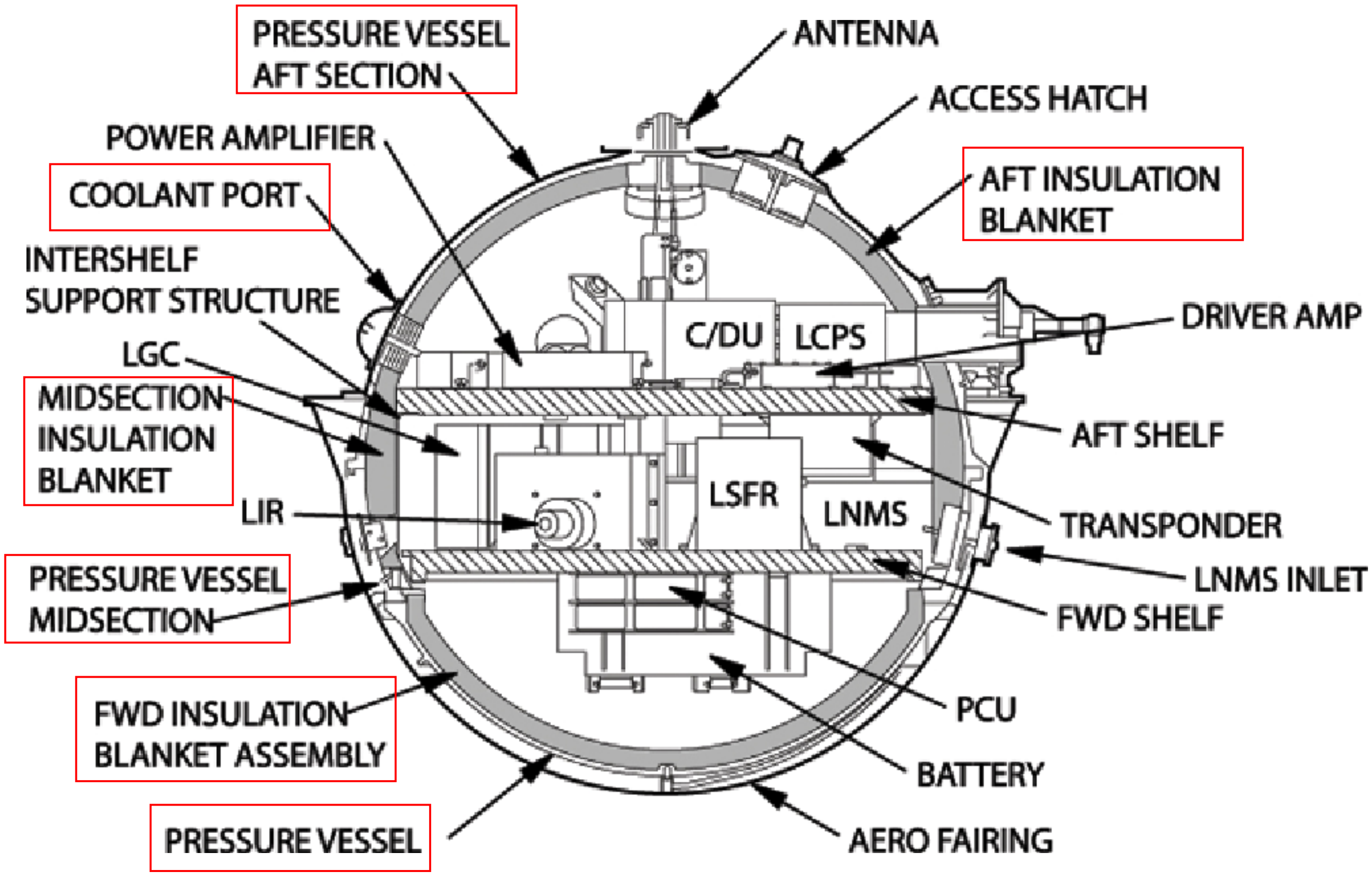
1. cover of parachute housing
2. drogue parachute
3. main parachute
4. altimeter antenna
5. **heat exchanger**
6. **heat accumulator**
7. **internal thermal insulation**
8. program timing unit
9. **heat accumulator**
10. shock absorbing damper
11. **external thermal insulation**
12. radio transmitter
13. spherical instrument compartment
14. commutation unit
15. **circulation fan**
16. **cooling conduit from bus**
17. ejectable secondary antenna
18. parachute housing
19. primary antenna
20. electrical umbilical
21. antenna feeder system
22. explosive bolts of cover
23. telemetry unit
24. stabilized quartz oscillator
25. commutation unit

Venera Instruments



Venera 13. A number of instruments were placed outside the pressure vessel. Ref. 1

Pioneer Venus Probe



Pioneer Venus Large Probe inside view of pressure vessel. Ref. 2

Pressure Vessel Systems

- Titanium successfully used on Venera and Pioneer Venus missions
- Structural shell must withstand 200 to 400 g deceleration loads during atmospheric entry
- Shell must also withstand pressure of 92 bar and temperature of 460°C
- Structural shell is the highest mass component of the Lander system…biggest opportunity for mass reduction
- Is there anything better than Ti out there?

6th International Planetary Probe Workshop, Atlanta, Georgia
Short Course on Extreme Environments Technologies
06/21-22 2008

Pressure Vessel Design Guidelines

- Buckling @ ultimate load of 150 atm pressure and 500ºC
  - use standard NASA specified knockdown factor of 0.14 for pressure vessels (0.3 is commonly used in industry).
- Yielding @ proof load of 125 atm pressure at 500ºC.
- Creep at 500ºC limit allowable total strain at 10 hours to 0.5%.
- Impermeable to gases
- Low thermal conductivity at 500ºC
- Compatible with Venus environment

Required Material Properties at Temperature

- Tensile/compressive yield strength
- Tensile elongation
- Shear strength
- Tension/compression modulus
- Fracture toughness
- Thermal conductivity
- Specific heat capacity
- Thermal expansion
- Creep rupture time
- Creep rate (in compression/bending)

Some Candidate Materials

- Metallic materials:
  - Titanium: Ti-6Al-4V alloy and Beta S
  - Nickel-chromium alloys: Inconel 718, Inconel X or Haynes 230
  - Nickel-chromium-cobalt alloys: Haynes 188
  - PH stainless steels: 17-7 PH or 15-5 PH
  - Beryllium I-220H
- Advanced composite materials:
  - SiC reinforced titanium matrix composites
  - B fiber reinforced titanium matrix composites
  - Inorganic Sialyte based composite
  - Aluminum/Sapphire and aluminum/silicon carbide metal matrix composites
  - Polymer Matrix Composite

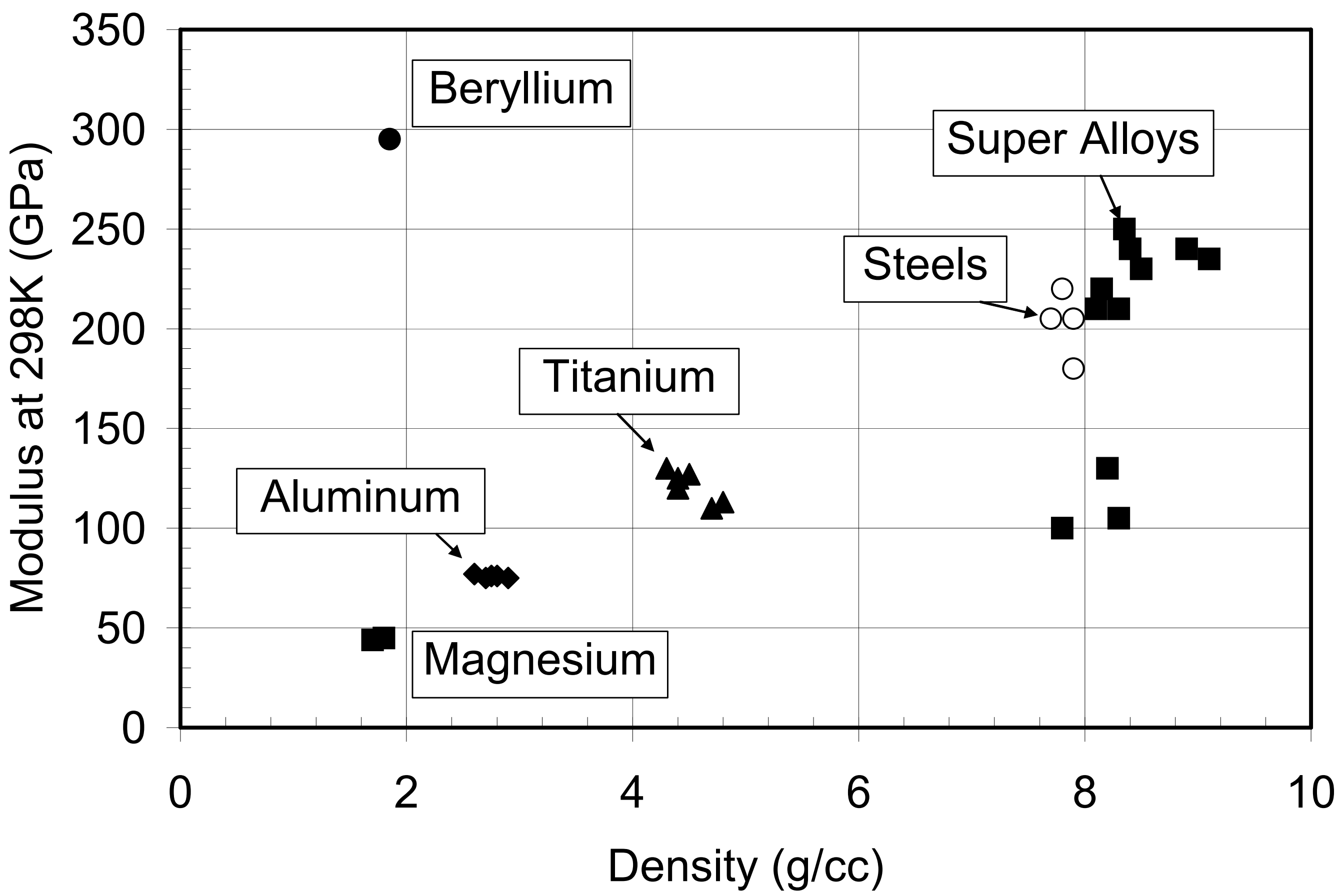
Material Trade Issues

- Inconel 718: best performance in both creep and tensile property comparisons
  - Primary metallic candidate for the pressure shell using honeycomb structure.
- Ti-6Al-4V: second best performer in creep and tensile comparisons also has low thermal conductivity.
  - State-of-the-art material on previous missions with monolithic shell.
- Haynes 188 has superior creep properties at high temperature. Performs best in 900°C to 1100°C range. At 500°C it is no better than Inconel 718.

Material Trade Issues

- 15-5 PH has reasonable creep properties at 500°C, but falls above 500°C leaving little margin.
- Creep data was not available for 17-7 PH. However it is not expected to perform significantly better than 15-5 PH.
- SiC/Ti matrix composite has superior strength/density performance compared to other materials. Creep resistant at 500°C.
- Beryllium is lightweight and has high elastic modulus, high thermal conductivity and high specific heat and low creep resistance in tension.

Material Trade Issues



Young's Modulus against density for various materials at room temperature. At 500°C the Magnesium and Aluminum alloys drop out.

Various Manufacturing Methods

Honeycomb Shell Construction

- Facesheets
  - Bulge-form Beta S titanium or Inconel 718 sheet to hemispherical shape.
- Honeycomb
  - Corrugate Beta S titanium or Inconel 718 sheet.
  - Diffusion bond corrugated sheet to form honeycomb block.
  - Slice honeycomb to desired thickness.
  - Bulge-form honeycomb to hemispherical shape.
- Assembly
  - Assemble facesheets, TiCuNi braze alloy or BNi-8 alloy, and honeycomb in hemispherical braze fixture
  - Vacuum furnace braze assembly.

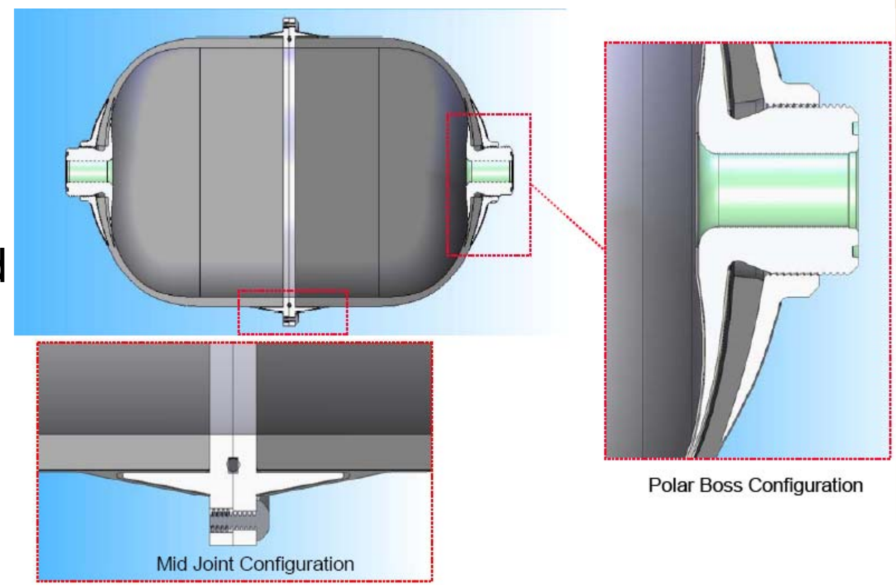
Bulge Form Tooling

Vacuum Braze Furnace

Various Manufacturing Methods

Composite Wrapped Tanks

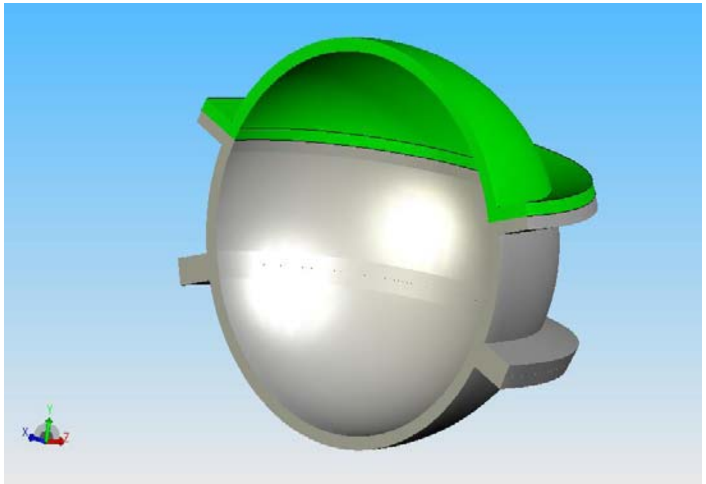
- Composite tanks using Aluminum/Sapphire or aluminum/silicon carbide or Polymer Matrix Composite
- Wrap matrix runs through wet adhesive such as molten aluminum or epoxy.
- Wetted matrix is wrapped around mandrel.
- Composite wound tank is cured at elevated temperature.
- Need to work out details of adding flanges, view ports, feed-throughs etc.



Various Manufacturing Methods

Monolithic Shells

- Titanium or Beryllium can be fabricated into monolithic shells.
- Titanium hemispheres can be shaped using spin forming.
- Flanges, windows, feed throughs, brackets etc can be welded onto the shell.
- Beryllium hemispheres must be machined from billets.
- Flanges, ports and other features must be machined into parent shell out of the original billet



Cut-Away sectional view of a 3 piece monolithic shell, similar to what was used on Pioneer Venus

Moving Forward

- Develop detailed manufacturing engineering plans for leading candidate materials.

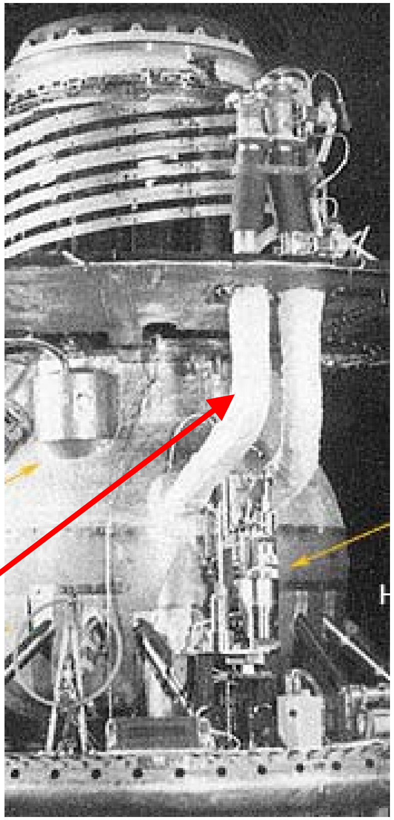
- Estimate comparative fabrication costs for the different manufacturing technologies.

- Obtain samples/prototypes of shells from leading candidate materials.

- Perform testing on prototypes under Venus-like environmental conditions for temperature and pressure for survivability.

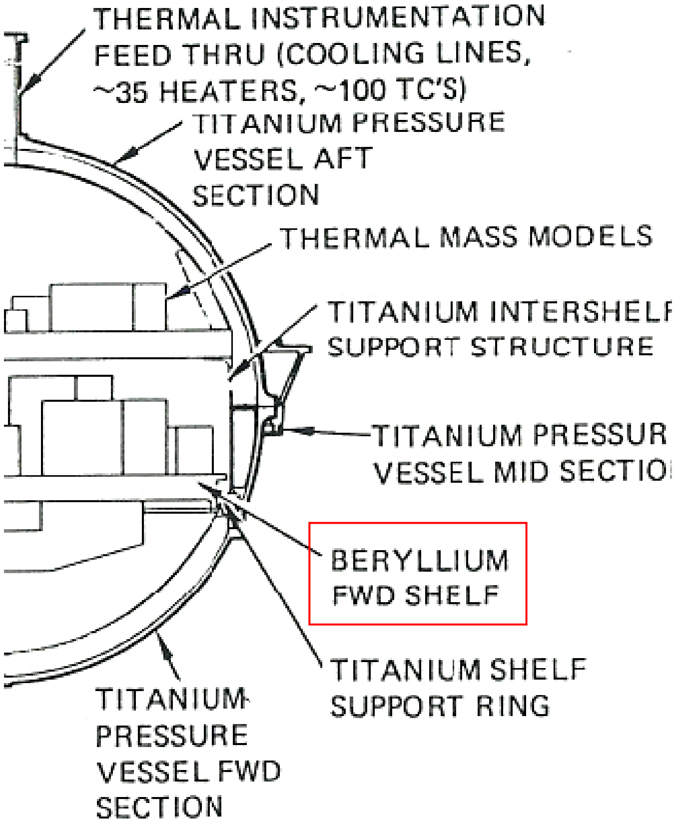
Thermal Control Systems

- Venera had external and internal insulation
- Used Lithium Nitrate phase change material for energy absorption
- Precooling of vessel interior prior to entry was used to maximize operating time.
- Venera had a cooling conduit from the spacecraft bus. Details unknown (probably was nitrogen gas system).



Thermal Control Systems

- Pioneer Venus had only internal insulation
- Heat absorbed by beryllium equipment shelves
- Precooling of interior prior to entry used a passive system, no external insulation, gas shorted MLI blankets inside vessel



Source: Ref. 3

Passive Thermal Control Strategy

- Assume internal components operate at typical s/c temperature limits…no special high temp limits
- For missions operating less than about 10 to 20 hours, passive thermal control is feasible
- Exterior insulation takes advantage of the thermal mass of shell
- Interior insulation with evacuated shell significantly increases lifetime
- Phase change materials and/or beryllium used to absorb internally generated heat

External Insulation

- **Zircar Ceramics MICROSIL Insulation**
- **Microtherm Super-G Insulation**
- **Thermal Ceramics Min-K**
- A combination of ultra-fine silica powders, specially processed refractory oxides and glass reinforcing fibers.
- Low density structure minimizes conductive heat transfer, nano-size pores block convection.
- Nearly immune to thermal shock. Completely non-combustible.

Porous Silica Insulation

Density: 230 to 400 kg/m^3

Conductivity: 0.026 to 0.033 W/m^2K at 500°C in air.

Needs testing in CO2

Internal Insulation

- Pioneer Venus used 41-layer MLI blanketing with N_2 or Xenon cover gas at 1 atm
- Although the MLI was thermally shorted by the gas it was an effective insulation for the mission < 1 hr
- Future missions may use less MLI with an evacuated vessel
- Internal radiation shield can be used to support MLI within the structural shell

An MLI Blanket

Thermal Energy Storage

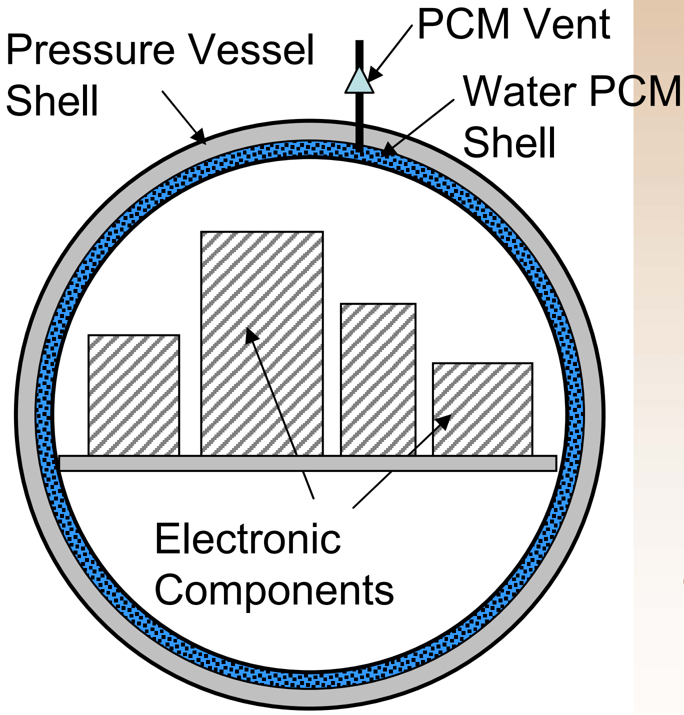
- Insulation prevents Venus environment from penetrating into the Lander
- Heat generated by electronics needs to be absorbed
- Beryllium is often used to store waste heat because it has a high heat capacity
- Phase change materials provide more capacity than beryllium

A beryllium component

Paraffin raw materials

Thermal Energy Storage

- Paraffin is a common storage media and is available in a wide range of temperatures
- Ice-water has the largest heat absorption per unit mass for a melt material
- Gas phase transitions absorb more heat than liquid transitions…but require higher temperatures
- Boiling point of water at Venus pressure is above 300ºC…could use to limit shell temperature
- Lithium nitrate has many desirable properties: high heat of fusion, high density, good melting point

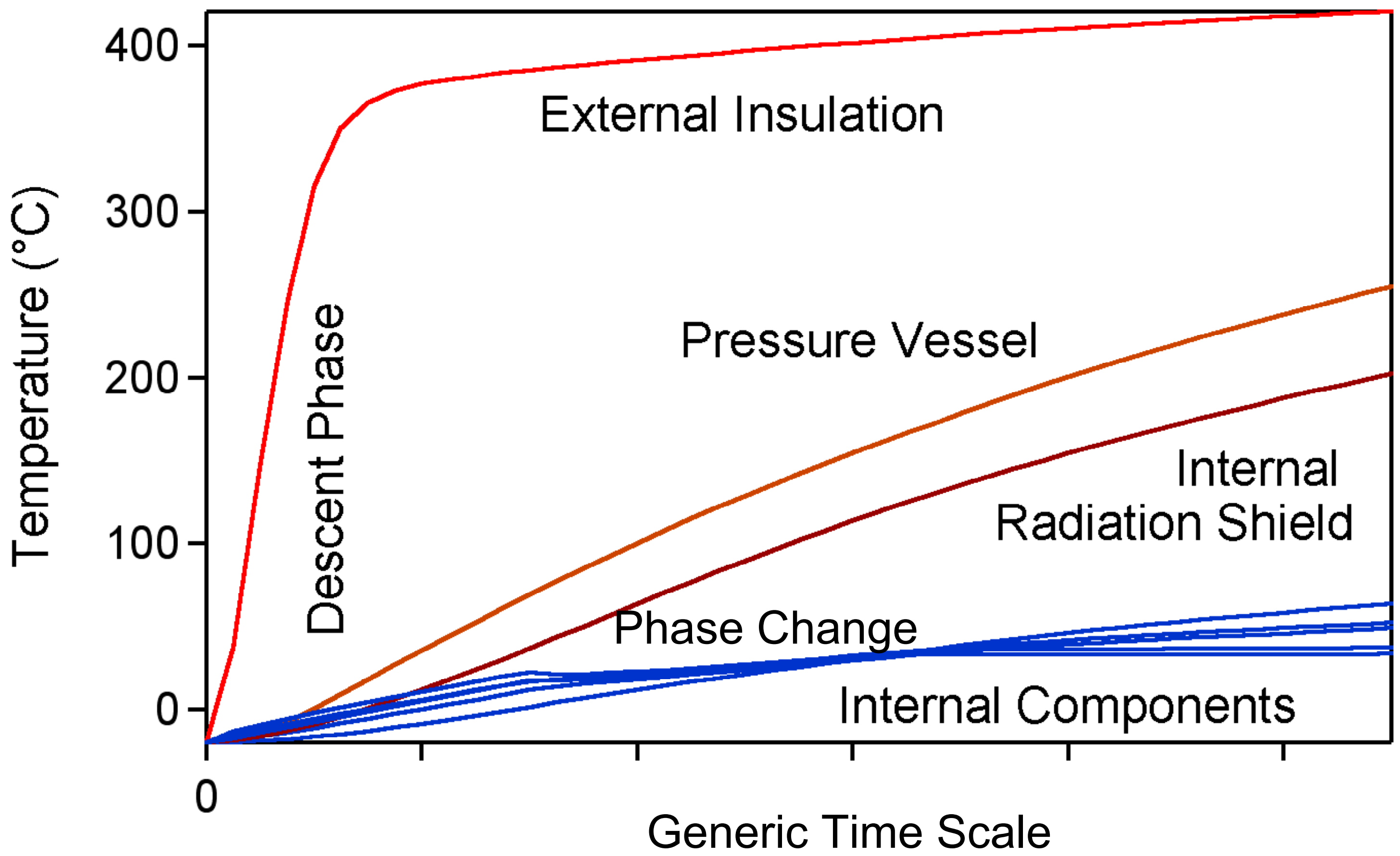


Thermal Energy Storage

Thermal property comparison of several phase change materials

Material	Formula	T_m (K)	T_m (C)	density (kg/m^3)		h_f (kJ/kg)	h_f' (MJ/m^3)
				solid	liquid		
water (melt)	H_2O	273	0	897	1000	333	299
lithium nitrate	**$LiNO_3{:}3H_2O$**	**303**	**30**	**1550**	**1430**	**296.5**	**460**
gallium	Ga	303	30	5900	-	80.3	474
sodium hydrogen phosphate	$Na_2HPO_4{:}12H_2O$	309	36	1520	1450	279.8	425
sodium hydroxide monohydrate	$NaOH{:}H_2O$	337	64	1720	-	272	468
cerrobend	alloy	343	70	9400	9200	33.4	314
barium hydroxide	$Ba(OH)_2{:}8H_2O$	351	78	2180	-	301	**656**
water (vaporize)	H_20	373	100	-	-	2260	**2260**
methyl fumarate	$(CHCO_2CH_3)_2$	375	102	1045	-	242	253
O-mannitol	$C_6H_{14}O_6$	439	166	1489	-	294	438
aluminum chloride	$AlCl_3$	465	192	2440	-	272	**664**

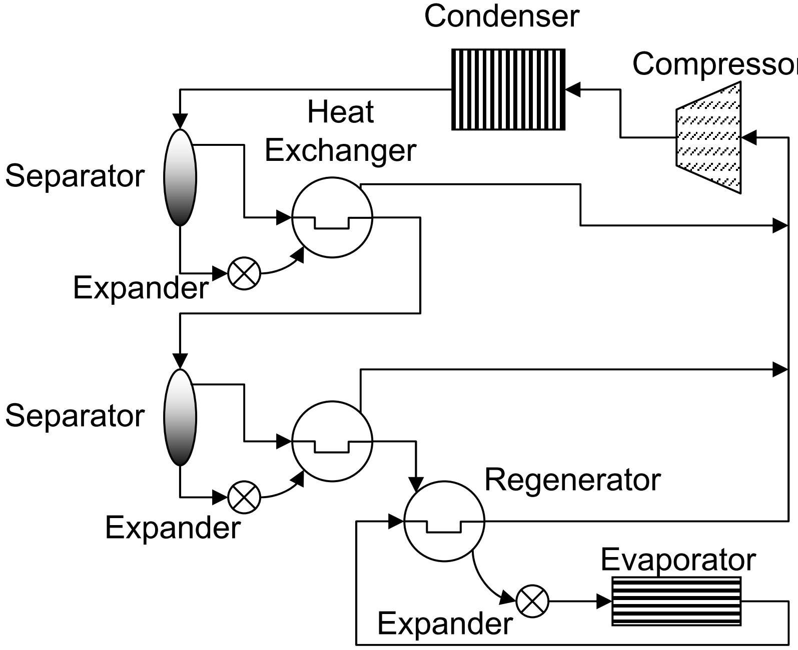
Desired System Thermal Response



Typical analytical results from a well designed thermal system

Active Thermal Control

- Survival beyond ~1 day will require high lift heat rejection capability.
- Efficiency is poor even for ideal Carnot cycle.
- Several concepts are available:
  - Thermoacoustic Refrigeration, 150ºC lift demonstrated LANL
  - Multistage Rankine/Brayton Refrigerator, 300ºC lift designed by Allied-Signal, efficiency estimated at 6%.



Summary & Conclusions

- Titanium has successful heritage as a structural shell for Landed Venus Missions
- Opportunities exist for reducing the shell mass but materials and processing development is required
- Passive thermal control techniques will enable missions to last up to around 10 to 20 hours
- Active thermal control is required to go beyond ~1 day of survival
- Significant development work is necessary for high lift heat rejection and long term, high capacity power systems

References

1. Kerzhanovich, V. and Pichkhadze, K., *Soviet Veneras and Mars: First Entry Probes Trajectory Reconstruction and Science,* International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Lisbon Portugal, 2003.

2. B. Bienstock, “Pioneer Venus and Galileo Entry Probe Heritage” International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, 6 – 9 OCTOBER 2003

3. L.A. Hennis and M.N. Varon, “Thermal Design and Development of Pioneer Venus Large Probe”, Paper 78-916, 2nd AIAA/ASME Thermophysics and Heat Transfer Conference, 1978.